

# Erosion of Rock and Soil

Best Practices in Dam and Levee Safety Risk Analysis  
Section D – Embankments and Foundations  
Chapter D-1

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US Army Corps  
of Engineers®



# Outline

- Objectives
- Key Concepts
- Erosion Process
- Rock Erosion Considerations
- Soil Erosion
- Takeaway Points



# Objectives

- Understand the input to methods and models for estimating erosion, and how it is obtained
- Be able to use this information as part of estimating the probability of erosion leading to failure under various potential failure modes
- (Estimating the probability of failure due to rock or soil erosion is covered in other chapters)



# Key Concepts

- Many potential failure modes require erosion of rock or soil to result in dam breach, such as:
  - Overtopping erosion of an embankment
  - Overtopping erosion of a concrete dam abutment or foundation
  - Erosion of an unlined spillway or river channel
  - Erosion of an unlined plunge pool (leading structural undermining)
  - Erosion of the spillway foundation where floor slabs have been damaged or lost
- Initiation of erosion does not equate to failure
- Judgement must be made concerning the progression of erosion over time (rate of erosion, duration of loading, progressive failure, etc.)
- It is important to consider erosion extent as well as the erosion potential

# Erosion Process



# How Erosion Starts

- Erosion can occur under high velocity flows which cause high soil/rock detachment/plucking rates
- A discontinuity exists which allows flow to concentrate, or changes the flow regime from sheet to turbulent
- Possible sources of discontinuities are:
  - Slope changes in downstream slope (flat slope changes to steep slope)
  - Obstacles such as trees, vegetation, guard rails, etc.
  - Bare spots in grass cover
  - Groins or abutments
  - Change in cover materials
  - Open pipes or channels through the soil





# Headcut Erosion Process

1. Flaw Exists in Protective Cover
2. Flow Concentrates and Surface Erosion Initiates at Flaw
3. Headcut Forms and Advances Upstream
4. Breach forms, if erosion and duration sufficient
5. (Note: if slope is composed of cohesionless soil, downward erosion may occur without a headcut forming first.) – but erosion mechanisms are more complicated.

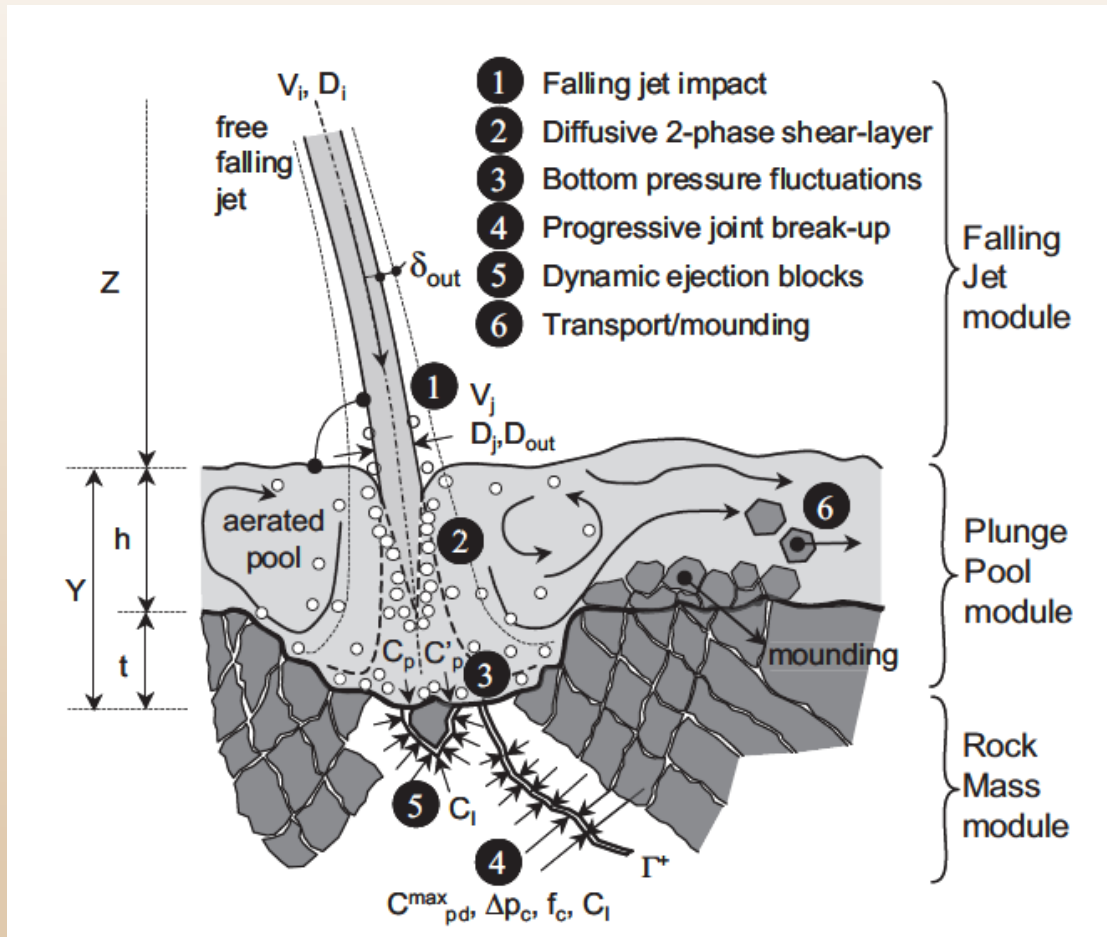


# Erosion Mechanisms





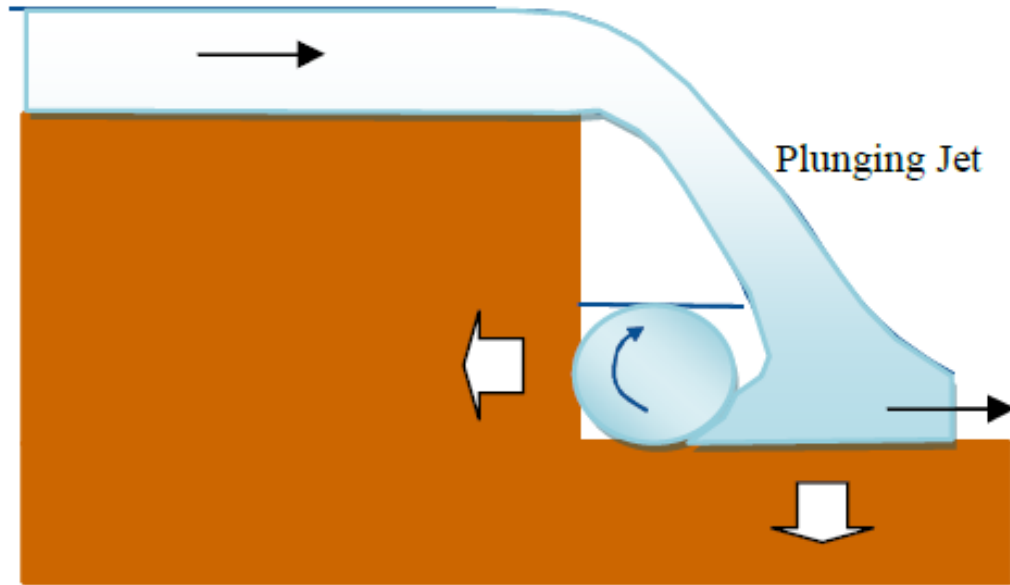
# Erosion/Scour Mechanisms (Plunging Jet)



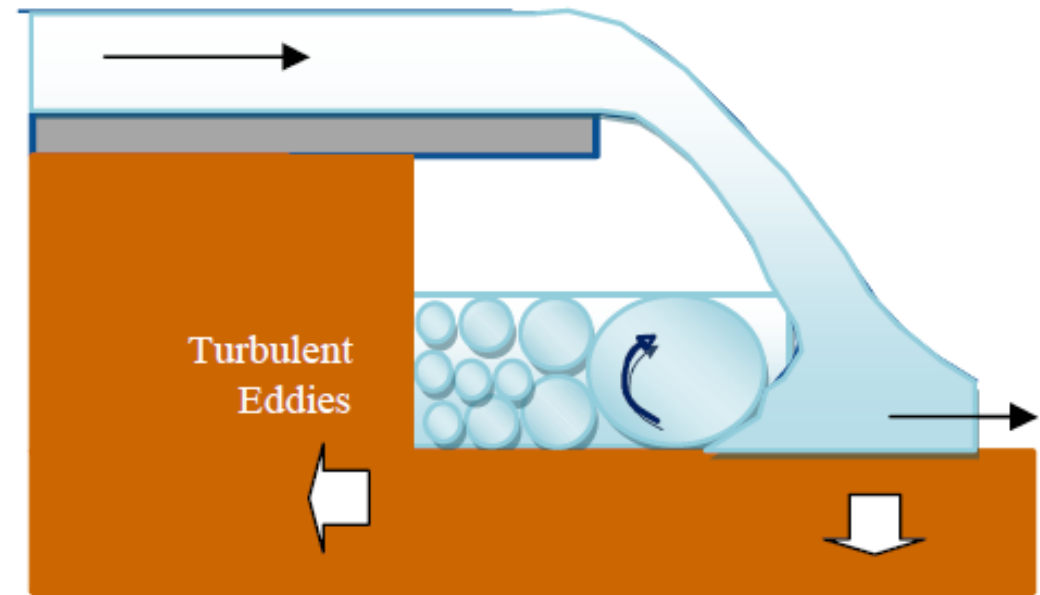
Bollaert (2010)

- Turbulence Production
  - Impinging Jet
  - Submerged Jet
  - Back Roller
  - Hydraulic Jump
  - Boundary Eddy Formation
- Particle Detachment (Cohesive Material)
  - Brittle Failure
  - Fatigue Failure
  - Block Removal (Ejection or Peeling)
  - Abrasion
  - Tensile Block Failure
- Particle Breakup/Transport
  - Armoring
  - Breakup
  - Transport

# Erosion Process (Back Roller/Headcutting)



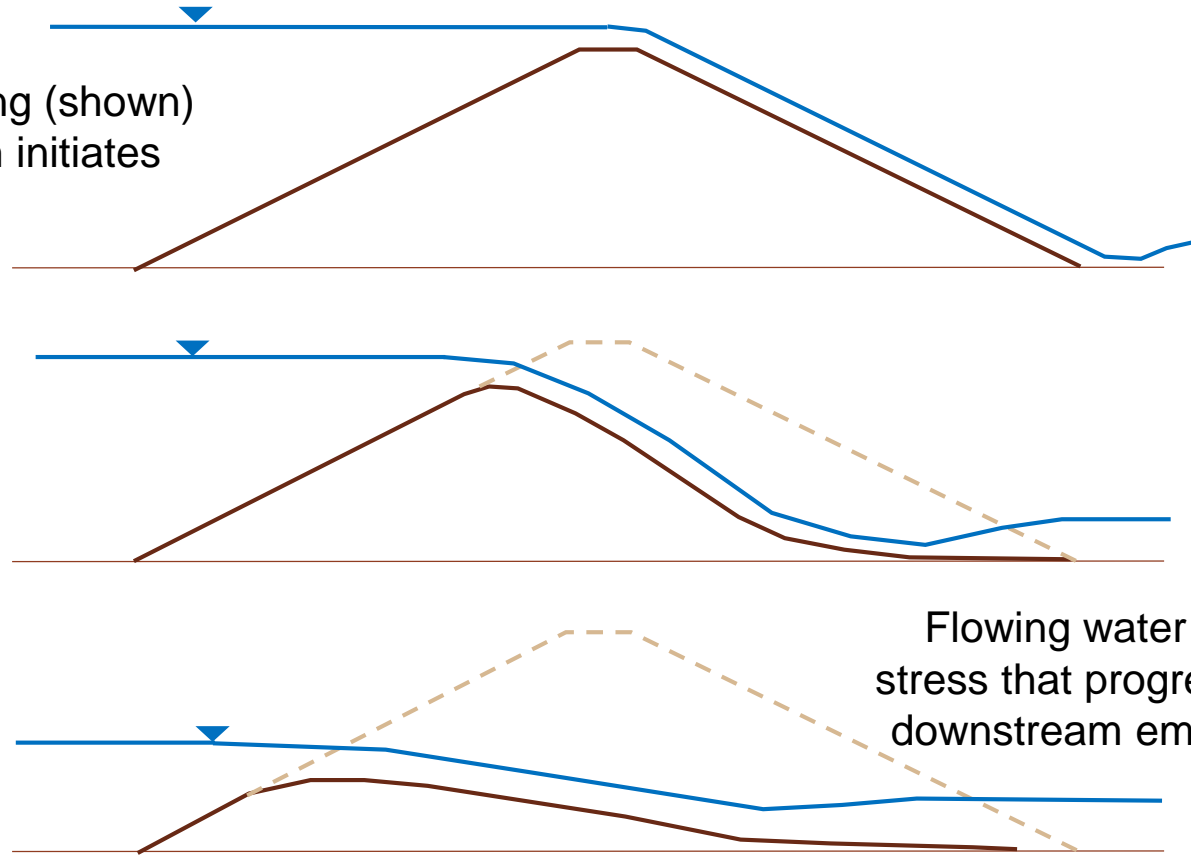
(a)



(b)

# Particle Detachment - Cohesionless Materials

Constant overtopping (shown)  
or wave overwash initiates



Flowing water induces a shear stress that progressively erodes the downstream embankment surface

# Armoring



# Rock Erosion



# Rock Erosion

- A few methods for estimating rock erosion exist:
  - Semi-empirical method developed by Annandale based on evaluating erosion resistance using a geotechnical erodibility index and erosion capacity based on stream power, calibrated to case studies
  - Physics based method developed by Bollaert which comprehensively evaluates fracture propagation as well as block movement, but currently assumes all rock blocks are cubic or rectangular in shape and lifting mode only
  - Block theory method developed by George which looks at the orientation and shape of the rock blocks, and flow velocities/pressures needed for their removal in a calculated failure mode, but currently is limited evaluating a few individual blocks
- The erodibility index method is currently used in the tools discussed in this course.





# Erodibility Index (also defines the Headcut Erodibility Index)

- Erodibility Index Method (Annandale 1995, 2006)
- Based on 150 field and laboratory case studies
- All types of earth materials represented
- Primarily used for rock in current practice

- Based on Kirsten's Rippability Index (1982) & Barton's Q System (1974)

$$K_h = M_s \cdot K_b \cdot K_d \cdot J_s$$

Resistance to fracturing

Resistance to block removal

$M_s$  = mass strength number ->  $f$ (Unconfined Compressive Strength, UCS)

$K_b$  = block size number ->  $f$ (Rock Quality Designation, RQD & # of joint sets)

$K_d$  = joint shear strength number ->  $f$ (joint roughness, alteration)

$J_s$  = joint orientation number ->  $f$ (joint strike dip)

# Stream Power

Stream power is calculated as a rate of energy dissipation

for example using the following for flow down a uniform slope:

$$P = \gamma U h S$$

$\gamma$  = unit weight of water

$U$  = flow velocity

$h$  = water depth

$S$  = hydraulic energy grade slope line

For a plunging jet (with no consideration for aeration, breakup, tailwater):

$$P = \gamma q H / d$$

$\gamma$  = unit weight of water

$q$  = unit discharge

$H$  = fall height

$d$  = thickness of the jet as it impacts foundation

material

For a back roller (no consideration for back eddies):

$$P = \gamma q_3 (v_m^2 / 2g)$$

$\gamma$  = unit weight of water

$q_3$  = unit flow rate in upstream direction

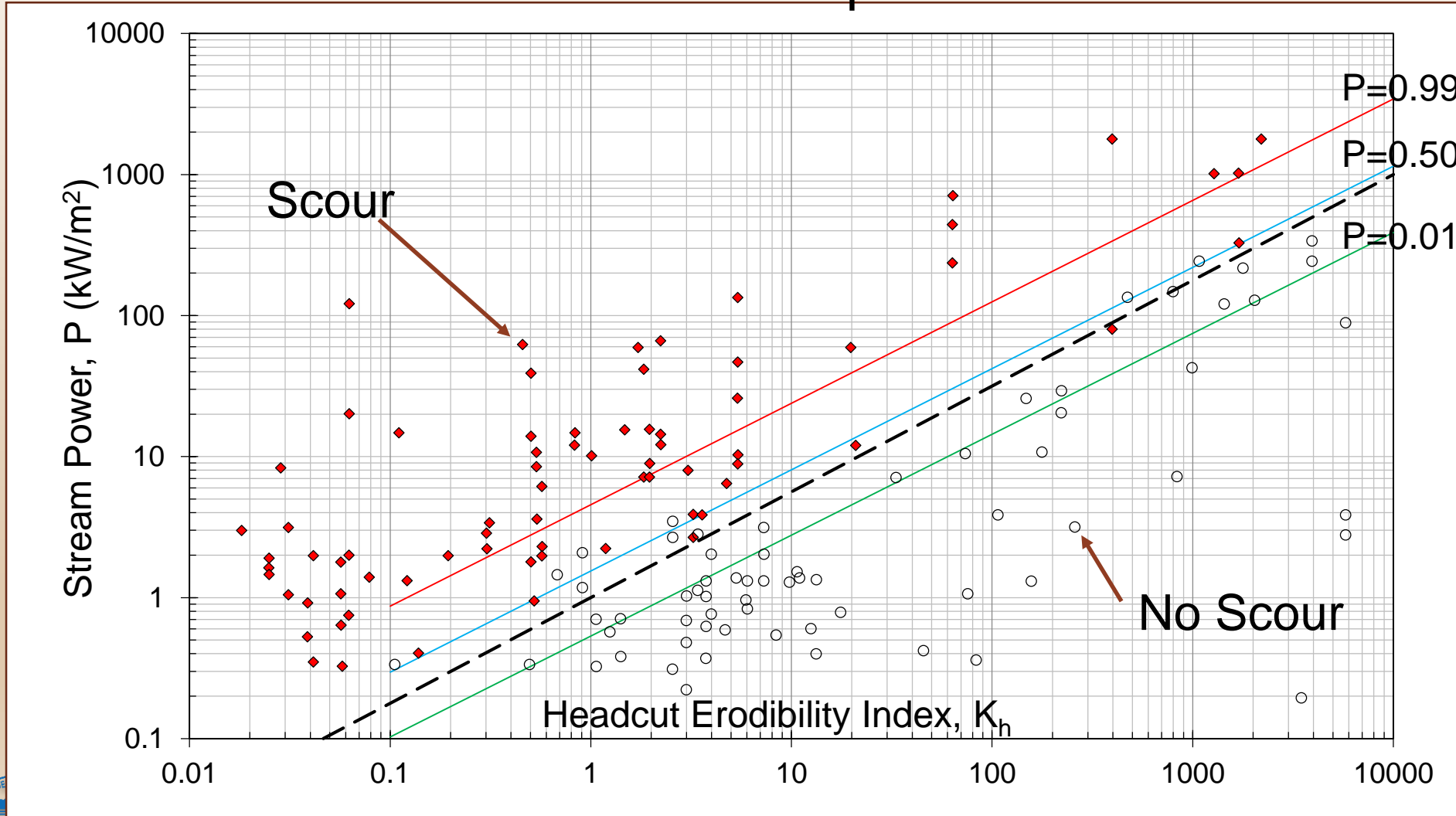
$v_m$  = average water velocity in pool

$g$  = acceleration due to gravity



# Erosion Potential

Stream Power and Headcut Erodibility Index, once determined, can be used to estimate the erosion potential



# Soil Erosion



# Soil Erosion

There are multiple variables to be considered when looking at erosion of soils:

- Flow Depth and Duration
- Shear Stress
- Flow Velocity
- Soil Material Type
- Geometry
- Armoring
- Vegetation
- Soil Properties (cohesion, particle size, density, water content etc...)



# Hydraulic Shear Stress for Surface Flow

Shear stress is often used to determine if a material will erode.  
In a channel or down a slope it can be defined as:

$$\tau_b = \gamma R_b S_e$$

$\gamma$  = *unit weight of water*

$R_b$  = *hydraulic radius of the bed*

$S_e$  = *energy slope*

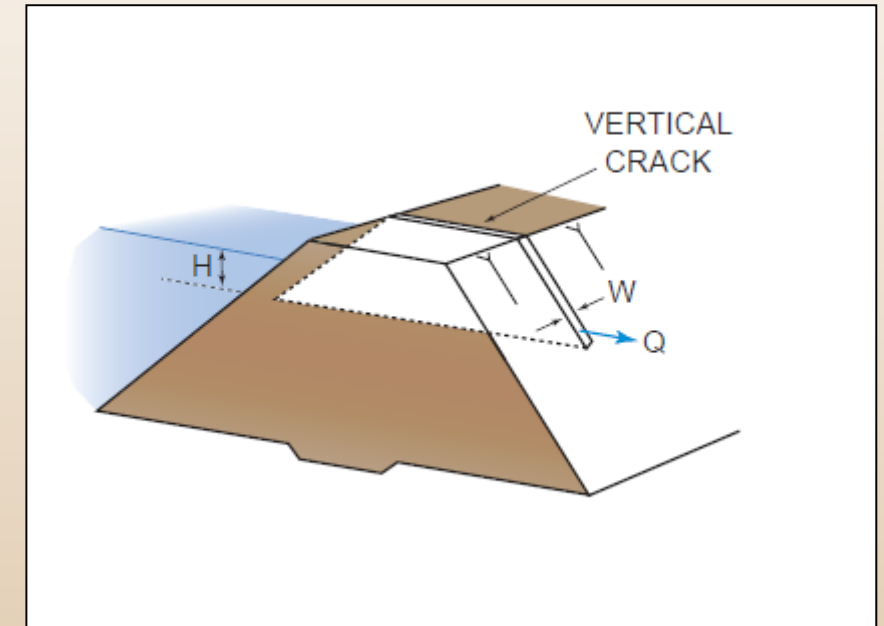




# Hydraulic Shear Stress in Crack or Pipe

$$\tau = \rho_w g (\Delta H/L) A / P_w$$

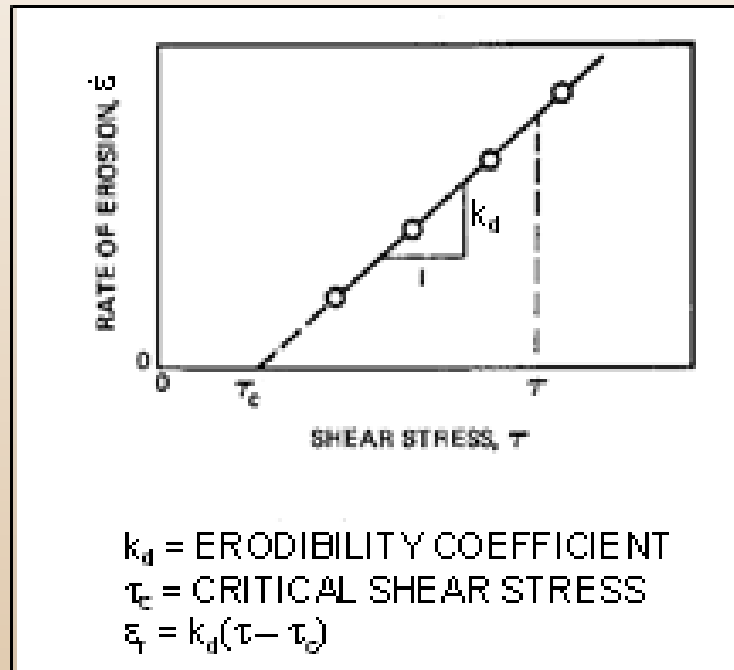
- $\rho_w$  = density of water
- $g$  = acceleration due to gravity
- $\Delta H$  = head loss in pipe or crack (due to friction)
- $L$  = length of crack or pipe base
- $A$  = cross-sectional area of crack or pipe
- $P_w$  = wetted perimeter of crack or pipe



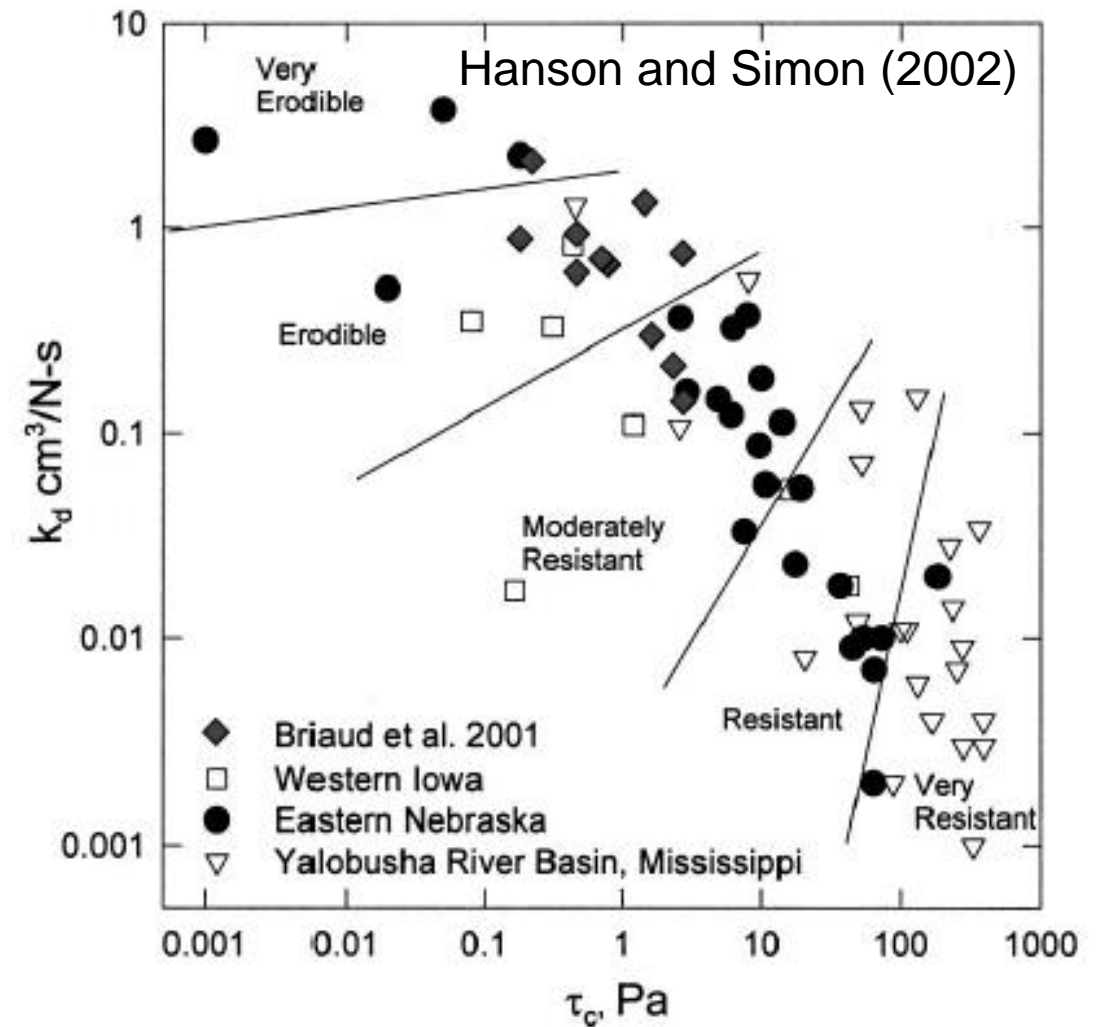
Since  $\gamma_w = \rho_w g$  and  $i = \Delta H/L$ , then  $\tau = \gamma_w i A / P_w$

Source: Wan and Fell (2004)

# Correlations For Estimating Soil Erosion Rate Parameters



Note: dispersive soils are a special class that may be extremely erodible and not represented on this chart.



# Erosion Laws

Volume Erosion:  $\varepsilon = k_d(\tau - \tau_c)$

- $\varepsilon$  = rate of volume of material removed per unit surface area per unit time (e.g., mm/hr)
- $\tau$  = hydraulic shear stress
- $\tau_c$  = critical shear stress
- $k_d$  = erodibility coefficient (typically  $\text{cm}^3/(\text{Ns})$  or  $(\text{ft/hr})/\text{psf}$ )

Mass Erosion:  $m = C_e(\tau - \tau_c)$

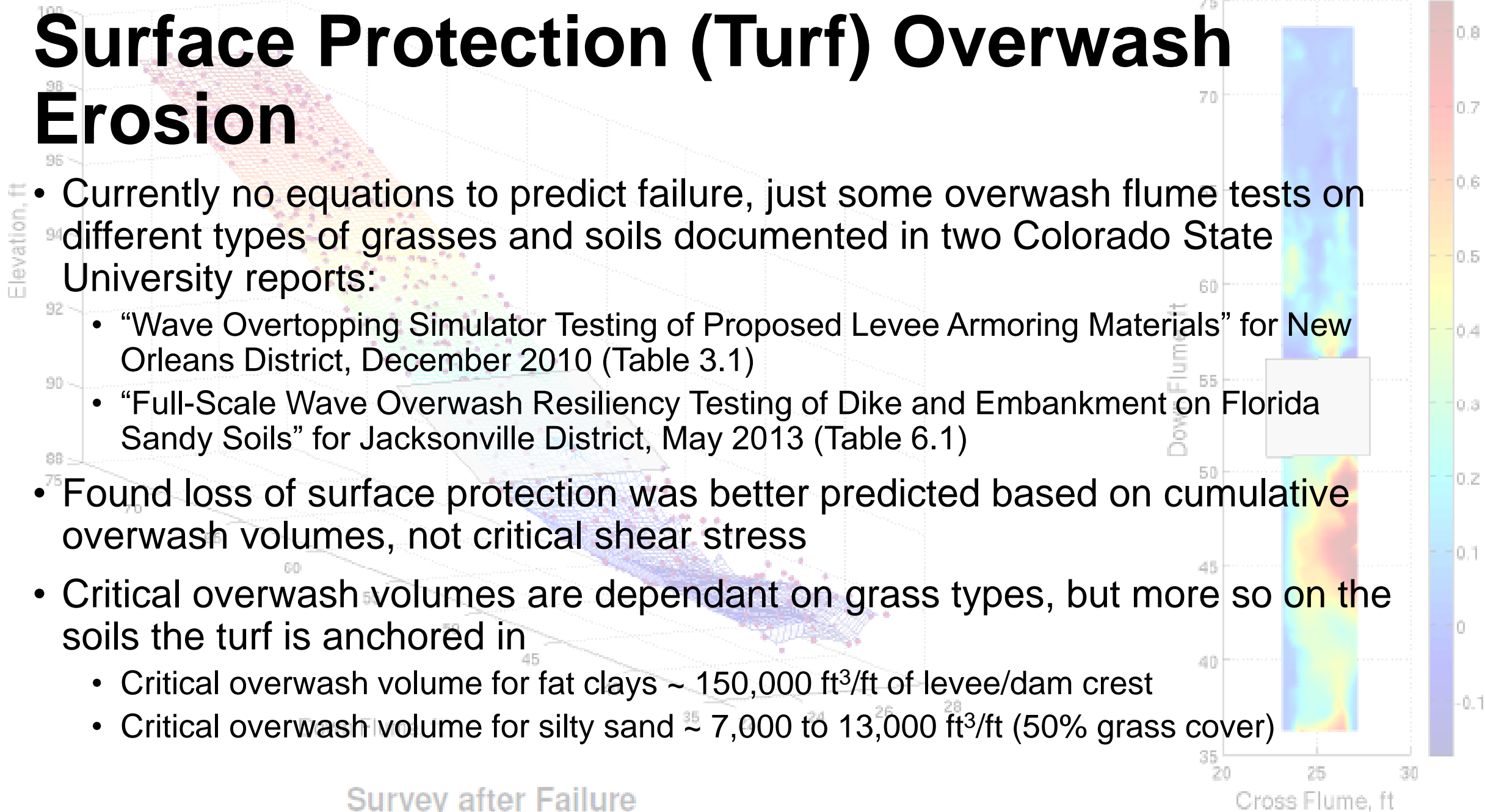
- $m$  = rate of mass removed per unit surface area per unit time (e.g.,  $\text{kg/s/m}^2$ )
- $\tau$  = hydraulic shear stress
- $\tau_c$  = critical shear stress
- $C_e$  = coefficient of soil erosion (typically s/m)
- $C_e = k_d(\rho_d)$

Source: Wahl et al. (2009)



# Surface Protection (Turf) Overwash Erosion

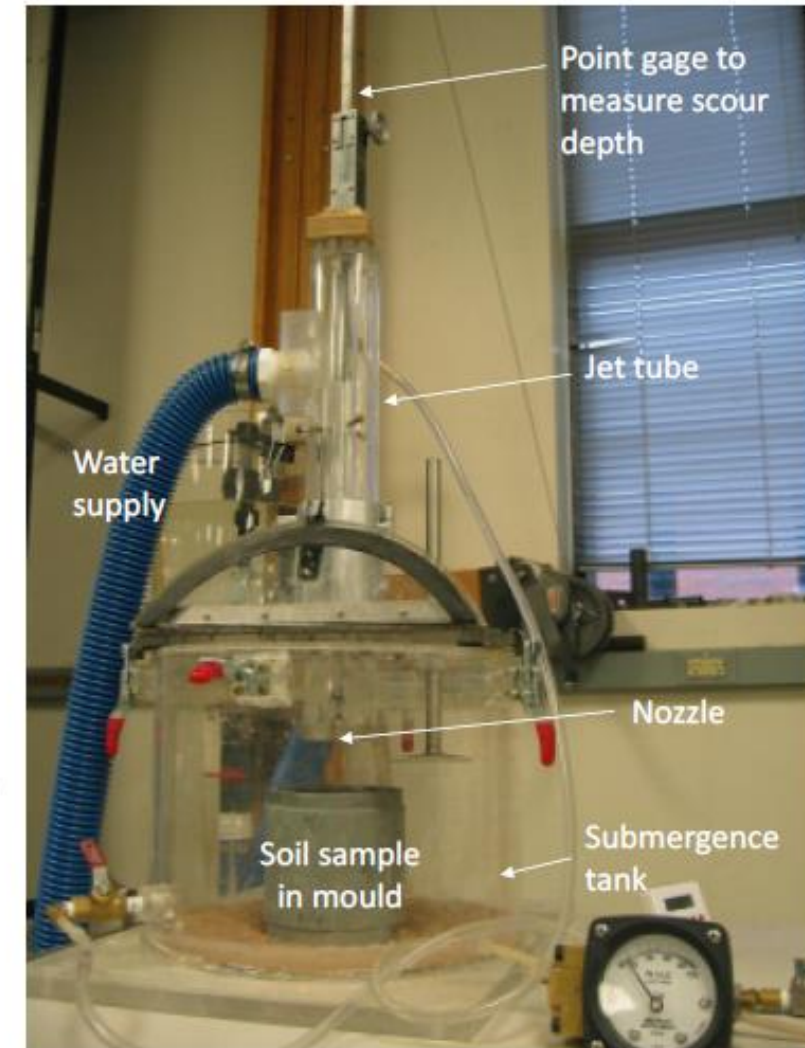
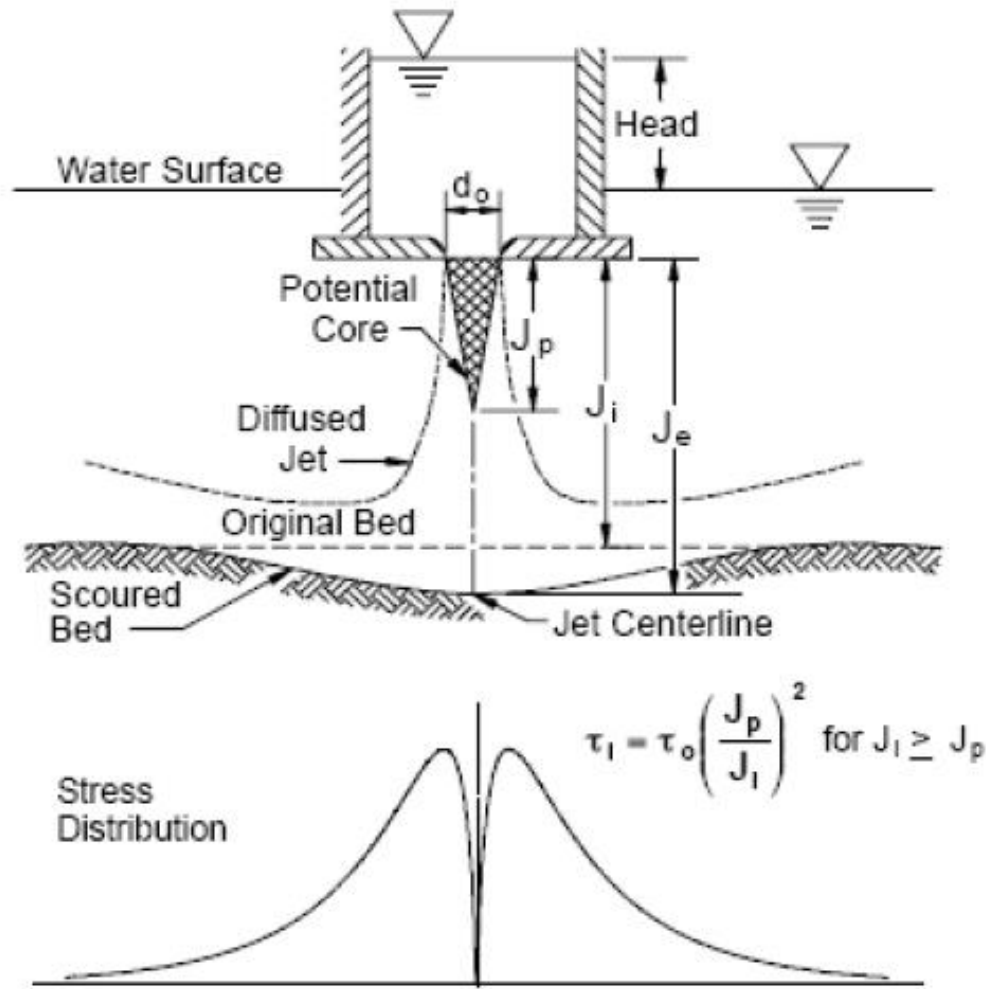
- Currently no equations to predict failure, just some overwash flume tests on different types of grasses and soils documented in two Colorado State University reports:
  - “Wave Overtopping Simulator Testing of Proposed Levee Armoring Materials” for New Orleans District, December 2010 (Table 3.1)
  - “Full-Scale Wave Overwash Resiliency Testing of Dike and Embankment on Florida Sandy Soils” for Jacksonville District, May 2013 (Table 6.1)
- Found loss of surface protection was better predicted based on cumulative overwash volumes, not critical shear stress
- Critical overwash volumes are dependant on grass types, but more so on the soils the turf is anchored in
  - Critical overwash volume for fat clays ~ 150,000 ft<sup>3</sup>/ft of levee/dam crest
  - Critical overwash volume for silty sand ~ 7,000 to 13,000 ft<sup>3</sup>/ft (50% grass cover)



# Soil Erodibility Tests

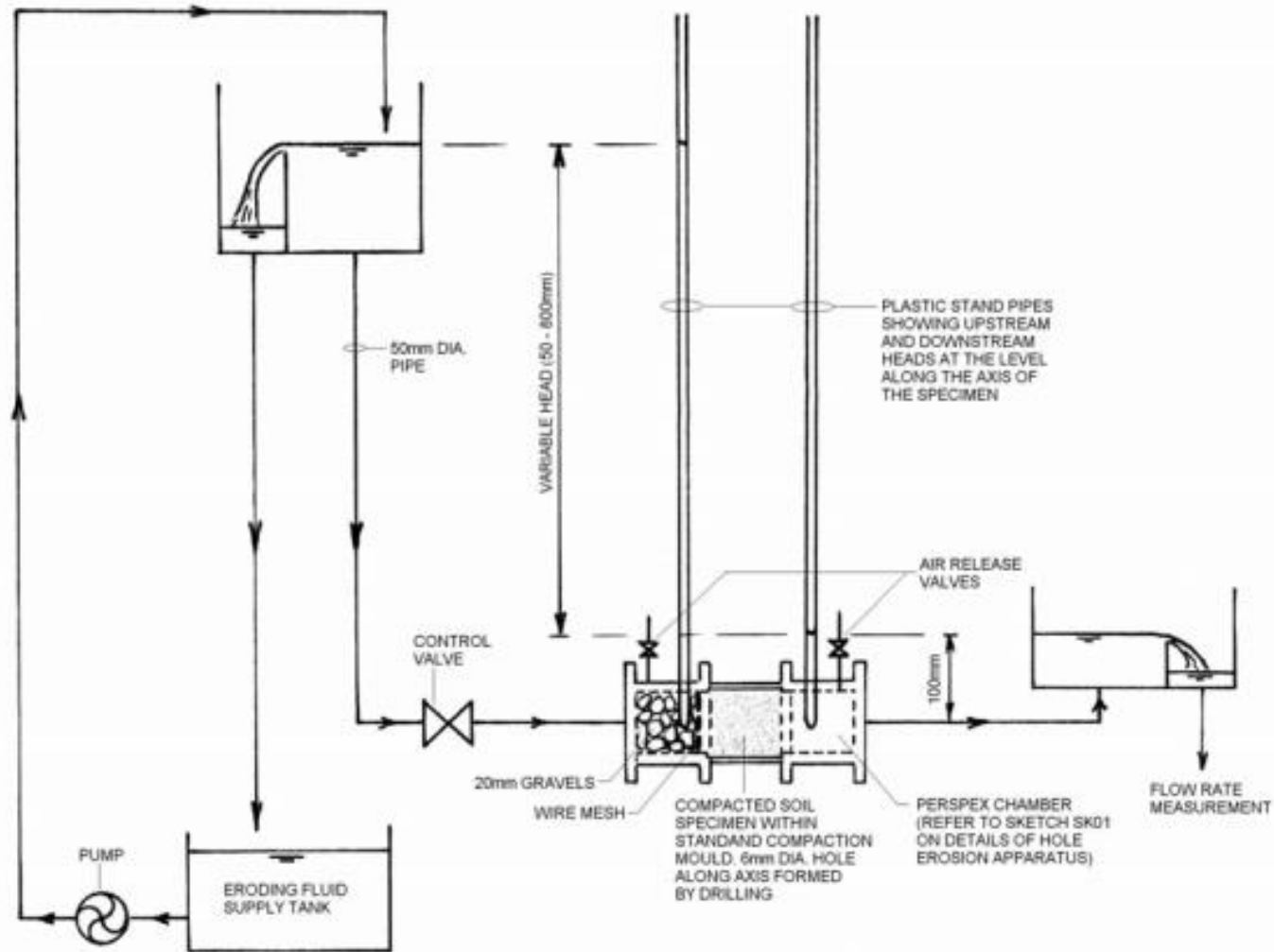


# Erosion Tests – JET Test

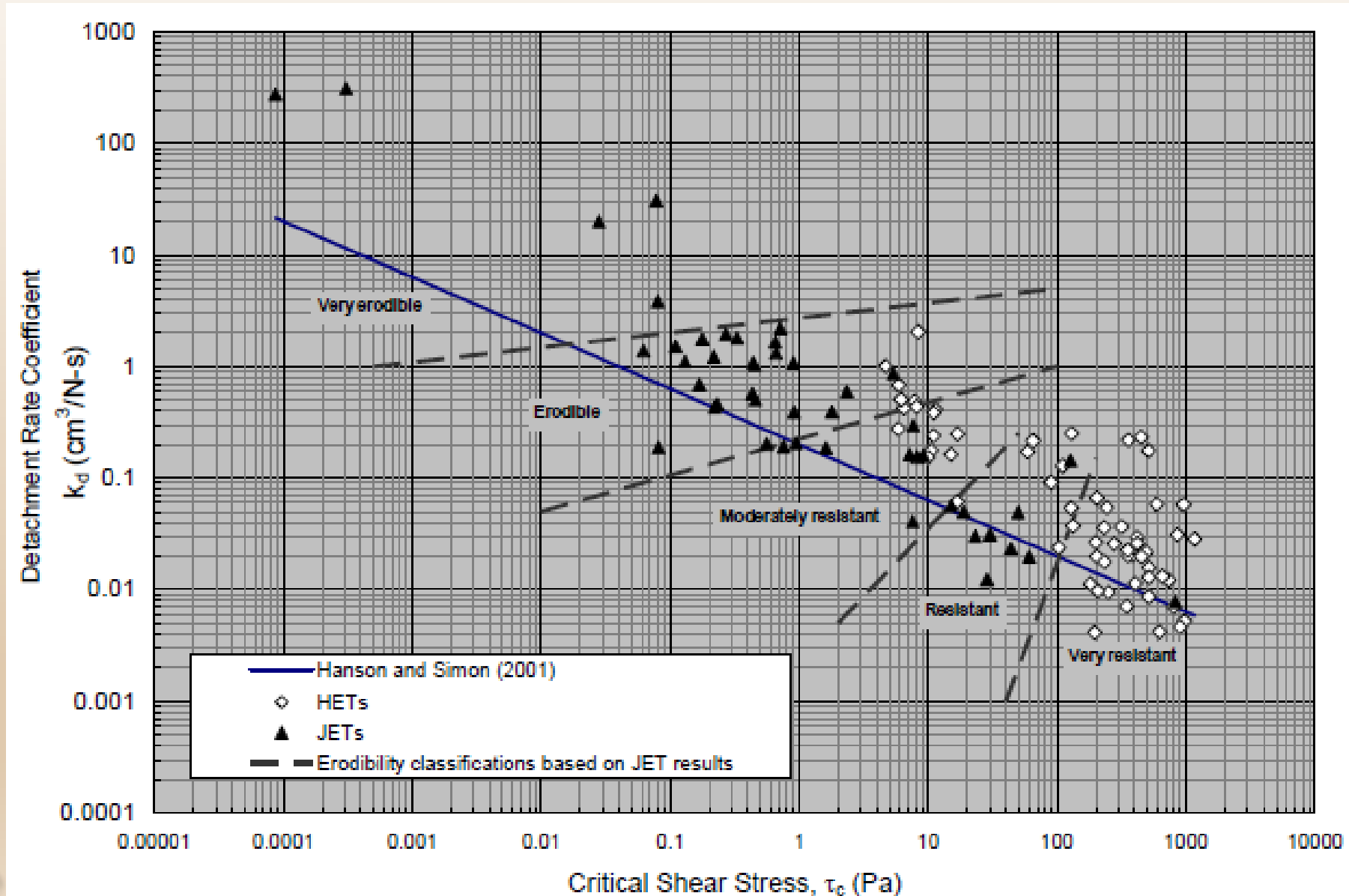




# Schematic of Hole Erosion Test



# Results for JET and HET from USBR



Wahl 2010

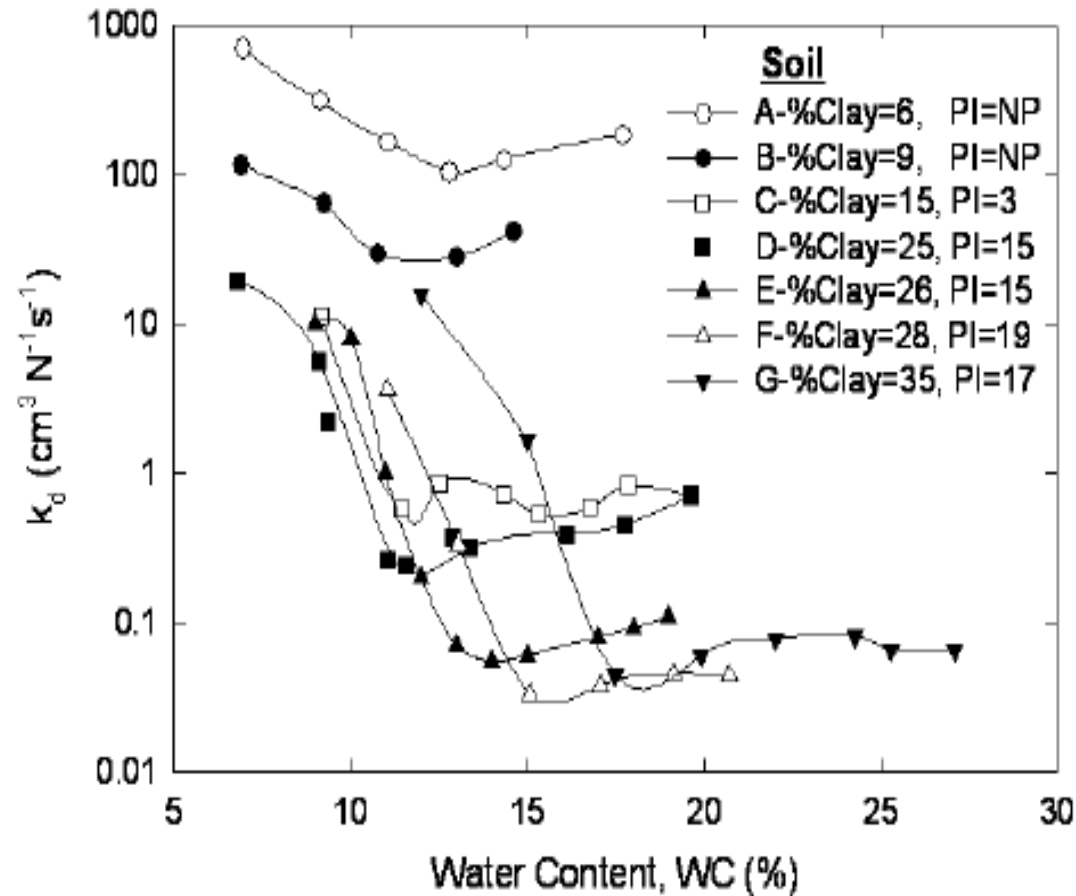
# Test Comparisons

- The relative erosion rankings are similar between HET and JET
- HET and JET produce significantly different erosion rates for a given shear stress, HET generally slower erosion
- Difference is most pronounced in “clumpy” soils
- HET appropriate for small opening such as concentrated leak internal erosion
- JET appropriate for overtopping or channel flow erosion
- JET works well with a broader range of soils
- WinDAM is calibrated to JET tests



# Factors Affecting Erosion Resistance

## Compaction Water Content



Soil Sample	USCS Classification	Atterberg Limits		Texture	
		Liquid Limit (%)	Plasticity Index (%)	% Sand > 0.074 mm	% Clay < 0.002 mm
A	SM	NP	NP	73	6
B	SM	NP	NP	64	9
C	ML	23	3	32	15
D	CL	26	15	35	25
E	CL	31	15	24	26
F	CL	37	19	20	28
G	CL	37	17	13	35

# Factors Affecting Erosion Resistance

## Plasticity?

○ SM – Silty Sand

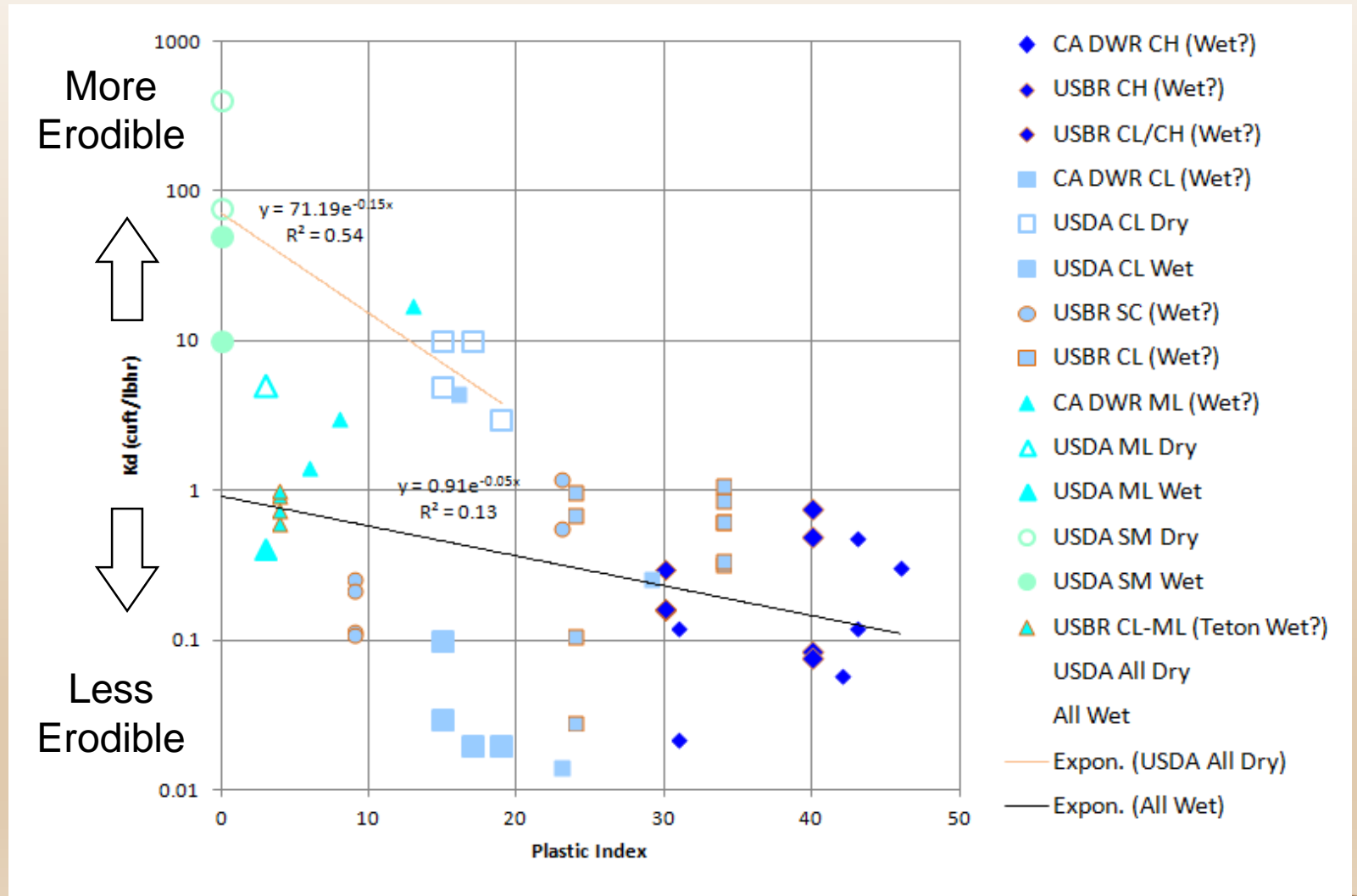
△ ML - Silt

□ CL – Lean Clay

◇ CH – Fat Clay

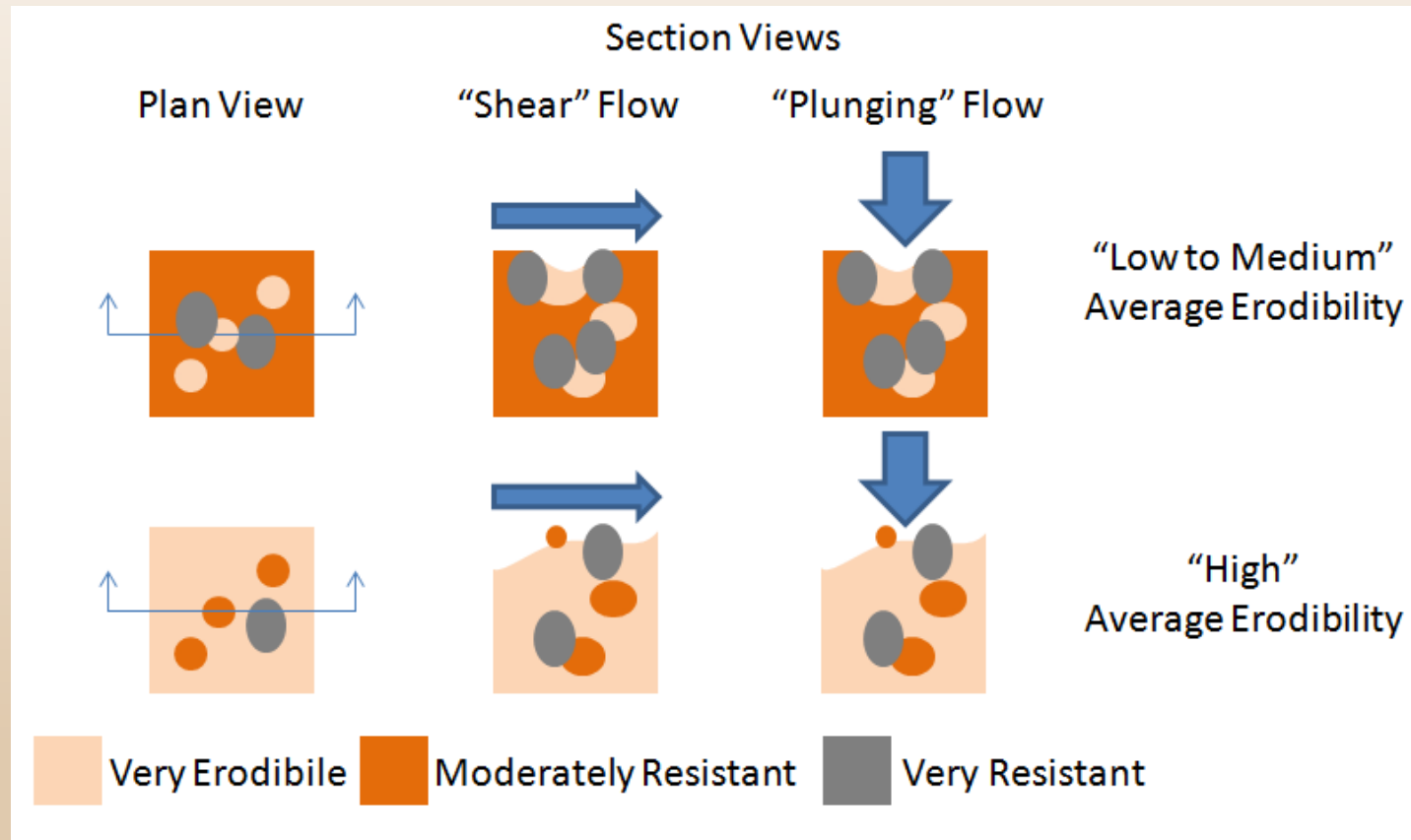
Filled shape: Wet of Optimum

Empty shape: Dry of Optimum



# Factors Affecting Erosion Resistance

## Proportion of Erodible and Resistant Materials





# Factors Affecting Erosion Resistance Native Materials

- Maximum Past Stress and Consolidation
- Cementation
- Wet/Dry Cycling
- Confinement
- Water Content when eroded (material curing)



# Modeling Erosion



# SITES

- Developed by USDA from observed Performance of Spillways to simulate headcut erosion in earthen spillways.
- Sites is a 1-Dimensional computer program that evaluates the stability and integrity of unlined channels using the three phase headcut erosion process. (It does not model a breach)
- The model run terminates when the headcut advances to the reservoir pool.
- The model was developed with a focus on soils, but has been applied to rock channels.
- SITES does not calculate breaches as flow and erosion are not coupled in the model.



# WinDAM C

- Developed by the USDA from research conducted at the Agricultural Research Service in Stillwater, Oklahoma
- Incorporate spillway erosion from SITES and includes algorithms for dam breach simulation (SIMBA)
- Will examine breaching due to overtopping of homogeneous embankments composed of cohesive materials (overtopping flow and erosion are coupled)
- Uses the same three phase erosion process, but adds in a fourth step which is breach development
- Will route flows through the reservoir (you supply an inflow hydrograph)
- Allows for variable dam crest elevations (camber)
- Allows flexible specification of the inflow hydrograph
- Detail provided in the model output is not as specific as that provided by SITES for spillway erosion
- Allows the user to enter multiple spillways



# Modeling things to remember...

- All models are wrong in some context; models are merely an oversimplification of reality and should be treated as such
- Geometry and flow are as important as erodibility and other factors. More than one alignment may be necessary.
- Input to the model will require data from a multi-disciplinary team.
- Want to run a full range of flows, duration is important.
- Kd and Kh can **HEAVILY** influence the output of these models
- Confront that issue explicitly:

**PERFORM SENSITIVITY  
ANALYSIS!**



# Modeling things to remember ctd...

- SITES and WINDAM may use terms that are familiar, but have different meanings, so it is important to understand what the program is referring to.
- Just because the model indicates that there is a potential for failure, does not mean that the model fails and vice-versa
- SITES cannot account for flow concentrations, variations in geometry (bends, cross slopes, changes in widths), etc.



# Takeaway Points

- Many potential failure modes feature progressive erosion of rock or soil leading to breach
- Initiation of erosion does not equate to failure/breach
- The resistance of rock to erosion is typically defined by the erodibility index (or headcut erodibility index) ( $K_h$ ).
- The resistance of soil to erosion is typically defined by the detachment rate ( $K_d$ ).
- Hydraulic studies are needed to determine the erosive capacity of the water impacting the rock or soil.
- Modeling will help estimate probabilities of erosion to breach

